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HIGH EFFICIENCY SILICON SOLAR CELLS

REPORT NUMBER III

THIRD QUARTERLY PROGRESS REPORT

REPORT DATE: April 15, 1963

PERIOD: December 15, 1962 to March 15, 1963

CONTRACT NO. DA 36-039-SC-90777

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ELECTRONICS RESEARCH AND DEVELOPMENT LABORATORY

FORT MONMOUTH, NEW JERSEY

HELIOTEK

DIVISION OF TEXTRON ELECTRONICS, INC.

12500 Gladstone Avenue

Sylmar, California

HIGH EFFICIENCY SILICON SOLAR CELLS

REPORT NUMBER III

Contract No. DA 36-039-SC-90777
Order No. 1091-PM-62-93-93(4213)

Third Quarterly Progress Report
Covering Period from December 15, 1962 to March 15, 1963

OBJECTIVE: INVESTIGATION FOR THE IMPROVEMENT OF
HIGH EFFICIENCY SILICON SOLAR CELLS
FOR TERRESTRIAL APPLICATIONS

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PURPOSE

The purpose of this contract is the development of high efficiency, low cost silicon solar cells. The objective is high yields, in the order of seventy (70) percent of the cells having efficiencies in the range of twelve to fourteen percent leading to a cell cost of \$2.00 to \$3.00 for a cell having dimensions of 1 cm by 2 cm. Both N+ on P and P+ on N cell structures are to be studied and the cells optimized for use in terrestrial environment with and without utilization of solar concentrators.

ABSTRACT

An additional mirror has been added to the solar concentrator equipment so that it is now possible to make solar cell measurements at approximately 5 gm-calories/cm^2 min solar intensity. The concentrator was used to verify the sunlight power predictions made from tungsten power measurements during the P^+/N bivariable experiment.

A general equation has been developed for the theoretical determination of the total cell series resistance from a knowledge of the values of the component resistances. The equations have been utilized to predict the series resistance of production type N^+/P and P^+/N cells. The predicted values were 0.73 ohms and 0.38 ohms for N^+/P and P^+/N cells respectively while the experimentally determined series resistance for high efficiency cells of these types were 0.74 ohms and 0.42 ohms respectively.

The results of bivariable experiments involving optimization of P^+/N and N^+/P cells for operations in a terrestrial environment under normal and concentrated solar intensities have been evaluated. On the basis of this analysis the optimum design for P^+/N cells requires a fifteen minute diffusion time and an eleven line grid pattern while the optimum N^+/P cell design requires an eighty minute diffusion time and an eleven line grid pattern.

Cells fabricated from p-type polycrystalline material having a resistivity of 10 ohm centimeters were evaluated for various cell designs. Cells having a sunlight efficiency greater than 9%, based on an active area of 1.8 square centimeters, were fabricated.

CONFERENCES

On 8 March 1963 a conference was held at Heliotek, Sylmar, California. The following personnel were present:

Representatives:
Dr. C. Daniel, Statistical Consultant for USAERDL
Dr. Mickey, Statistical Consultant

Heliotek:
M. Wolf
E. L. Ralph
P. Berman

During this conference the applicability of statistical experiments in the optimization of solar cell processes were discussed. Methods of data presentation and analysis were also discussed, as well as the design of future polyvariable experiments.

INTRODUCTION AND SUMMARY

An additional mirror has been added to the solar concentrator system described in the First Quarterly Progress Report increasing the maximum solar intensity obtainable in the system to about 5 cal cm^{-2} min^{-1}. Tests made during this period showed that all four mirrors concentrated light uniformly over the working area within the concentrator with an intensity variation of less than 1.5 percent.

The solar concentrator was used in order to verify the sunlight power predictions made on the basis of tungsten measurements during the P^+/N polyvariable experiment described in the Second Quarterly Progress Report. It was found that the zero, one, and three mirror concentrations gave intensities quite close to the 100, 163, and 316 milliwatt per square centimeter intensities utilized in the polyvariable experiment. Of the five cells measured in natural sunlight, four of them were within about five percent of the predicted power at each of the intensity ranges. The fifth cell was fifteen percent lower than the predicted power at the 163 and 316 milliwatt per square centimeter intensities. Series resistance measurements made from data taken at the time of the tungsten measurements and later at the time of the sunlight measurements showed that an increase in series resistance of about 0.35 ohms had occurred between the time of the two measurements, so that the discrepancy between predicted sunlight power and measured sunlight power was primarily due to cell degradation.

Work has been continued on the theoretical determination of solar cell series resistance. An improved equation has been developed to replace equation (3-13) which was developed in the First Quarterly Progress Report and which was valid only for a unit cell. The improved equation is valid for a complete cell. Minimum values for the resistances R_4 and R_5, the resistance of the diffused layer for carriers flowing to

the contact strip and grid strip respectively, have been calculated for five line gridded N^+/P and P^+/N production type cells. These values were utilized along with the experimentally determined values for the other component resistances in the improved series resistance equation in order to theoretically predict the total cell resistance. The theoretical prediction for N^+/P cells and P^+/N cells were 0.73 ohms and 0.38 ohms respectively (the N^+/P cells being fabricated from 10 ohm centimeter material and the P^+/N cells being fabricated from approximately one ohm centimeter material). Experimental determinations of the series resistance of high efficiency production cells show resistances of 0.74 ohms and 0.42 ohms for N^+/P and P^+/N cells respectively, indicating very good agreement with the predicted values.

The results of the P^+/N cell bivariable experiment have been analyzed to determine the optimum diffusion time and number of grid lines for operation in a terrestrial environment under normal and concentrated solar intensities. A number of figures are presented showing the isopower curves generated on the three dimensional surface determined from the maximum power per unit intensity at each of the experimental design points. The figures show that the surface is increasing towards the upper right portion of the design matirix, indicating that the shorter diffusion times and higher grid line numbers tend towards the optimum. On the basis of the surfaces, it has been decided to utilize a fifteen minute diffusion time and an eleven line grid pattern in the fabrication of the 500 pilot line P/N type cells to be produced during the next quarter. It is fortunate that the optimum at the higher solar intensities seems to be compatible with the optimum design for normal solar intensities, so that conceivably, one cell design will suffice for both cases.

A bivariable experiment has been conducted in order to determine the optimum diffusion time and number of grid lines appropriate to N^+/P type solar cells for concentrated and unconcentrated terrestrial use.

Material having a base resistivity of about one ohm centimeter was used in the fabrication of these cells. A method for the determination of the maximum power per unit solar intensity from tungsten measurements similar to that used in the previous polyvariable experiment was utilized. The multiplicative constant used to obtain the sunlight maximum powers from the tungsten measurements, which is obtained from the ratio of the cell short circuit currents in sunlight and tungsten light, showed unexpected characteristics. The multiplicative constant seemed, for the most part, to be very insensitive to the junction depth variations, indicating that the spectral responses were not varying significantly with junction depth. This was further verified through direct spectral response measurements. One explanation might be that due to the fact that phosphorus (the diffusant for N^+/P cells) is a better match for the silicon lattice than boron (which is the diffusant for P^+/N cells), the trapping levels introduced by the phosphorus atoms are less severe. If the minority carrier diffusion length is greater than one micron in the diffused region, the response from this region may not be too sensitive to junction depth variation up to about one micron. Also variations in the silicon monoxide antireflectance coatings may be a major factor in the variation of spectral response. On the basis of the experimental results it was decided to utilize an eleven line grid pattern and an 80 minute diffusion in the fabrication of the pilot line N^+/P cells.

A number of polycrystalline cells have been fabricated from p-type polycrystalline material having a resistivity in the ten ohm centimeter range. The highest power in the sunlight of approximately 100 milliwatts per square centimeter intensity was obtained for twenty minute diffused cells with silicon monoxide anti-reflection coatings applied. The sunlight efficiencies based on an area of 1.8 square centimeters were about nine percent. It was determined that the silicon monoxide coatings were not optimized to the spectral response of these cells. It was also determined that the twenty minute diffusions were superior to forty-five minute diffusions, although the decrease of efficiency

with increasing junction depth was not nearly as great as had been observed previously for low resistivity P^+/N cells. Cells having five and ten line grid patterns were compared, but there was no clear superiority of one pattern over the other.

CONCENTRATED SUNLIGHT MEASUREMENTS

During this report period an additional mirror was added to the concentrator system described in the First Quarterly Progress Report in order to attain higher solar intensities through increased concentration. The new mirror is a 6" x 20" aluminum evaporated, front surfaced plane mirror, as are the original three mirrors.

It was necessary to insure that the mirror concentrated sunlight uniformly over the working area within the concentrator. It was decided at this time to recheck the uniformity of the other three mirrors as well. The uniformity check was accomplished by means of a panel of seven cells soldered to a copper plate approximately five inches square. The cells were positioned in such a manner as to represent as much of the working area as possible. One of the cells was utilized as a reference standard, and use was made of the following relationship:

$$\frac{I_{sc}(1)}{I_{sc}(2)} = \frac{I'_{sc}(1)}{I'_{sc}(2)} \qquad (2\text{-}1)$$

where the $I_{sc}(1)$ and $I_{sc}(2)$ represent the short circuit current of a cell at intensities (1) and (2) respectively. The primed quantities on the right side of the equation represent the short circuit current of another cell at the same intensities (1) and (2). This relationship assumes that the short circuit currents of the cells are directly proportional to the incoming intensity. The standard cell was measured immediately preceding a measurement of each of the other cells. Measurements were made in the unconcentrated condition (all mirrors in a non-contributing position) and with each of the mirrors rotated into a contributing position. The concentrated - non concentrated short circuit current ratio of each of the cells was then compared with the ratio of the standard short circuit currents as measured immediately prior to the cell measurement. The results are presented in Table II-1. Mirror #1 is the new mirror and the ratio of the concentrated-unconcentrated

UNIFORMITY CHECK FOR CONCENTRATOR MIRRORS

TABLE II-1

	I	II	III	IV	V	VI	VII	VIII	IX
Cell No.	I_{sc} 0 Mirror	I_{sc} Mirror #1 (New Mirror)	$\frac{I_{sc_1}}{I_{sc_0}}$ $\frac{II}{I}$	I_{sc} Mirror #2	$\frac{I_{sc_2}}{I_{sc_0}}$ $\frac{IV}{I}$	I_{sc} Mirror #3	$\frac{I_{sc_3}}{I_{sc_0}}$ $\frac{VI}{I}$	I_{sc} Mirror #4	$\frac{I_{sc_4}}{I_{sc_0}}$ $\frac{VIII}{I}$
Stnd	60.8	101.7	1.69	102.8	1.69	104.2	1.71	103.2	1.69
1	58.0	96.8	1.67	97.9	1.69	98.5	1.70	98.3	1.69
Stnd	61.4	101.7	1.67	102.3	1.67	103.5	1.71	103.5	1.71
2	60.3	100.5	1.68	101.2	1.68	102.0	1.70	102.0	1.70
Stnd	61.2	101.5	1.68	102.8	1.69	103.5	1.70	104.0	1.70
3	60.0	99.8	1.67	100.8	1.68	100.7	1.68	101.3	1.68
Stnd	61.2	101.0	1.66	101.5	1.67	103.9	1.71	103.0	1.69
4	54.8	90.4	1.64	92.5	1.69	92.9	1.69	92.7	1.69
Stnd	61.1	100.8	1.66	103.0	1.69	103.8	1.70	103.5	1.70
5	47.8	79.5	1.67	80.5	1.69	81.9	1.71	82.0	1.71
Stnd	61.1	100 8	1.66	103.0	1.69	104.4	1.71	103.0	1.69
6	49.0	81.2	1.65	82.7	1.69	84.2	1.71	83.8	1.71

short circuit currents for this mirror are shown, as indicated, in column III. It can be seen from the table that the mirrors provide a uniform concentration across the working area of less than 1.5 percent variation.

It was also found that the maximum solar intensity obtained when all four mirrors were in the contributing position was in the range of 360 milliwatts per square centimeter (approximately 5 gm cal/cm^2 min).

During the last report period a polyvariable experiment was performed on P/N type cells involving the variation of diffusion time and number of grid lines. The figure of merit utilized in the analysis of the results was the maximum power output per unit solar intensity. The measurements were made under tungsten light and a degradation factor was utilized to predict the corresponding power output per unit solar intensity from the tungsten measurements. In order to obtain a verification of the accuracy of this procedure, five of the cells involved in the polyvariable experiment were soldered to a copper plate which was mounted on the water-cooled plate inside the concentrator, and complete current-voltage curves were obtained at various concentration levels under natural sunlight in Sylmar, California.

It was found that the zero, one and three mirror concentrations corresponded rather well to the 100, 163, and 316 milliwatt per square centimeter intensities utilized in the experiment. The results of the experiment are shown in Table II-2. Column I shows the short circuit current of the standard cell. Column II shows the solar input in milliwatts obtained by multiplying the short circuit current of the standard cell by the cell constant of 1.8 milliwatts per milliamp. Column III shows the maximum power output as determined from the current-voltage curves.

TABLE II-2

COMPARISON BETWEEN PREDICTED POWER/SOLAR INTENSITY
AND MEASURED POWER/INTENSITY (P^+/N POLYVARIABLE EXPERIMENT)

	I	II	III	IV	V	VI
Cell No.	Standard Reading (mA)	Power In I x 1.8 (MW)	Power Out mW	Power at 100 mW Sun $\frac{III \times 100}{II}$	Power at 100 mW as Predicted	Ratio $\frac{IV}{V}$
0 MIRROR						
22-1	56.0	100.8	21.5	21.3	21.3	1.00
22-6	57.0	102.6	21.5	21.0	22.6	.92
-5	57.5	103.5	23.5	22.7	23.1	.98
-2	57.0	102.6	22.5	21.9	22.8	.96
-6	56.5	101.7	20.5	20.2	21.4	.94
				Power at 163 mW Sun $\frac{III \times 163}{II}$	Power at 163 mW	
1 MIRROR						
22-1	89.0	160.2	35.0	35.6	38.0	.93
22-6	93.0	167.4	35.2	34.3	39.6	.86
25-5	92.0	165.6	36.0	35.4	36 9	.95
26-2	88.0	158.4	35.0	36.0	36.9	.97
28-6	89.0	160.2	32.0	32.6	33.8	.96
				Power at 316 mW Sun $\frac{III \times 316}{II}$	Power at 316 mW	
3 MIRROR						
22-1	161.0	289.8	66.0	72.0	75.6	.95
22-6	159.0	286.2	59.0	65.1	74.8	.87
25-5	162.5	292.5	54.5	58.9	62.1	.94
26-2	155.0	279.0	58.5	66.3	68.4	.96
28-6	159.0	286.2	51.0	56.3	56.3	1.00

Cell 22-1 = 5 minute 10 grid
Cell 22-6 = 5 minute 6 grid
Cell 25-5 = 20 minute 3 grid
Cell 26-2 = 30 minute 8 grid
Cell 28-6 = 40 minute 3 grid

It will be noticed that the data is separated into groups corresponding to the zero, one, and three mirror combinations. Column IV shows the power output at the zero, one and three mirror configurations corrected to correspond to intensities of 100, 163, and 316 milliwatts per square centimeter respectively. Column V shows the maximum power output at the various intensities as predicted from the tungsten measurements. Column VI shows the ratio of the power as actually measured in sunlight to the power as predicted from the tungsten measurements. It can be seen from Column VI that the predicted power was always somewhat optimistic, since the ratio is never greater than one. With the exception of cell number 22-6, the predicted values are compatible with the measured values to within about five percent. Cell number 22-6 shows a discrepancy of about fifteen percent at the 163 and 316 milliwatt per square centimeter intensities.

It was unusual that cell 22-6 should show such a large deviation from the predicted value, especially in light of the fact that cell 22-1, which was diffused for the same length of time and had exactly the same degradation factor, showed good agreement with the predicted power at all intensities. Therefore series resistance measurements were made on these cells and compared with the value calculated from the original tungsten measurements. It was found that the series resistance had increased from approximately 0.45 ohms to approximately 0.8 ohms for cell 22-6. This indicates that sometime between the tungsten measurements and the sunlight measurements this cell became degraded through a series resistance increase of about .35 ohms, which probably occurred when the cells were soldered to the mounting plate.

The four mirror concentrator system was used to obtain the maximum power values at a solar intensity of 350 mW/cm^2 for several of the P/N cells in order to observe the effect of the increased illumination on the max power/intensity for the various cell configurations. The maximum power

per unit solar intensity of the five cells as measured under intensities of 316 and 350 mW/cm^2 are shown below:

Cell No.	P_{max}/Int at 316 mW/cm^2	P_{max}/Int at 350 mW/cm^2
22-1	.228	.224
22-6	.206	.198
25-5	.186	.172
26-2	.210	.204
28-6	.178	.170

It can be seen that there is only a 4% additional decrease in P_{max}/Intensity in going from 316 to 350 mW/cm^2 and that the decrease is fairly uniform for all the cells (between .004 and .008) so that the results obtained for the 316 mW/cm^2 intensity are also applicable to 350 mW/cm^2 intensity.

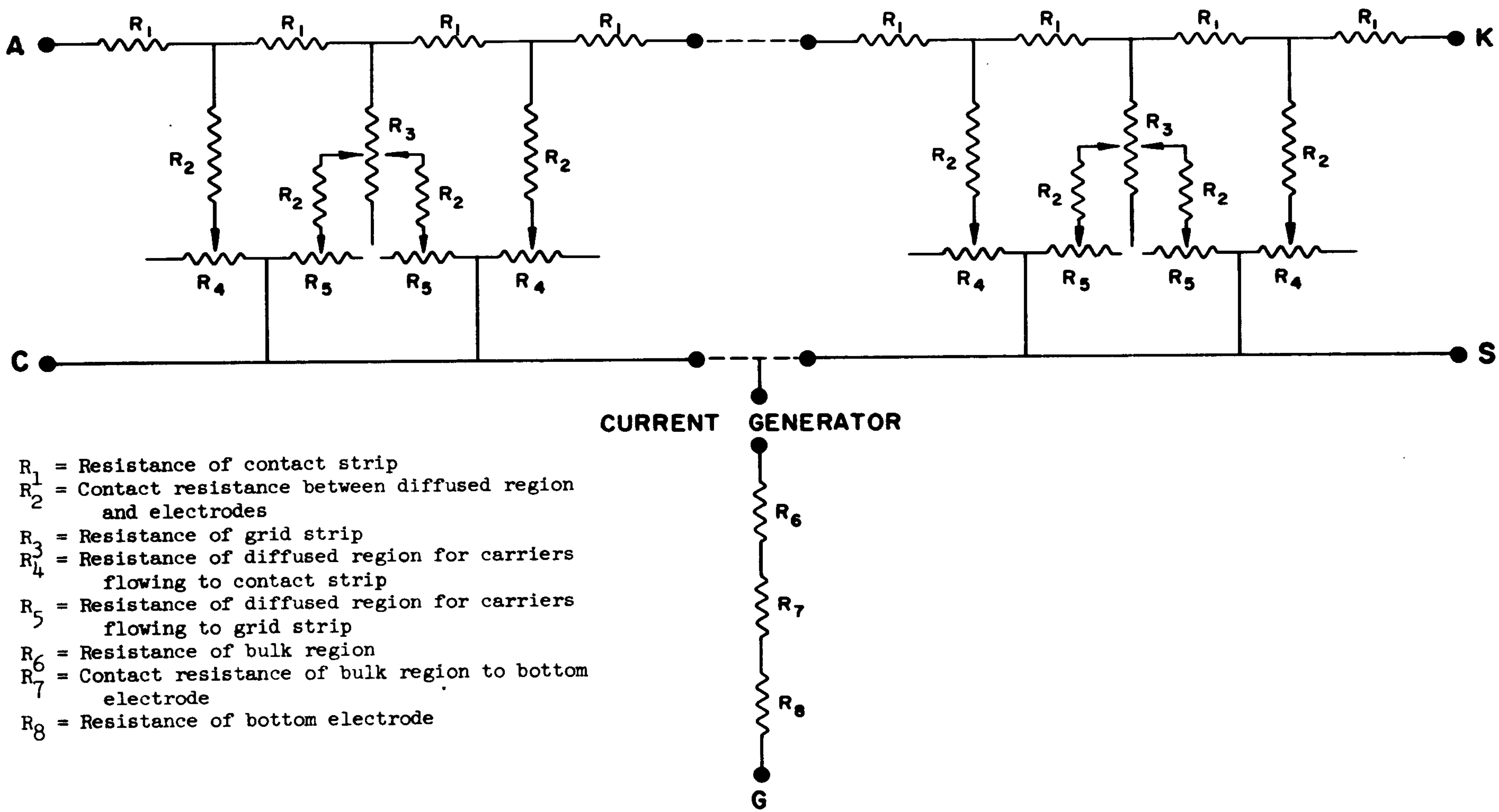
SERIES RESISTANCE EFFECTS AND GRID OPTIMIZATION

During this report period the minimum value of resistance R_4 and R_5, the resistance of the diffused layer for carriers flowing to the contact strip and grid strip respectively, were calculated for a spacing between grids of 2/5 centimeters (corresponding to a standard, five grid line 1 x 2 square centimeter cell). These resistances were calculated for both N^+/P and P^+/N cells utilizing a sheet resistance of 40 ohms for the former and 24 ohms for the latter type. The left hand (lower) limits of the following equations (Eqs. (35) and (36) from the Second Quarterly Progress Report) were used for the determination of minimum value of R_4 and R_5 respectively:

$$\cos \theta_1 \left(\frac{2\rho}{St r_3}\right) \int_0^{r_3} r dr \leq R_4 \leq \frac{2\rho}{St r_3} \int_0^{r_3} r dr \quad ; \tag{3-1}$$

$$\sin \theta_1 \left(\frac{2\rho}{St(2W - r_3)}\right) \int_0^{r_3} r dr \leq R_5 \leq \frac{2\rho}{St(2W - r_3)} \int_0^{r_3} r dr \quad ; \tag{3-2}$$

where from the geometry $\theta = 28°24'$. The values of R_4 and R_5 for the N^+/P case were found to be 27 ohms and 3.8 ohms respectively, while for the P^+/N case R_4 and R_5 were 16.2 ohms and 2.3 ohms respectively. These values can then be applied to the total series resistance as was described in the First Quarterly Progress Report, Eqs. (3) to (13). It must be remembered that this equation represented the total series resistance for a unit cell. However, in the determination of the total series resistance for a cell which is larger than a single unit (as is generally the case) the equivalent circuits of each of the unit cells must be added in parallel. The number of parallel equivalent circuits will always be equal to the number of grids applied to the cell. The paralleled combinations must be added in series with the resistances R_6, R_7 and R_8 of the base region. The schematic figure representing the equivalent circuit of an n-unit cell is shown in Fig. 3-1. Through analysis of this circuit an equation



R_1 = Resistance of contact strip
R_2 = Contact resistance between diffused region and electrodes
R_3 = Resistance of grid strip
R_4 = Resistance of diffused region for carriers flowing to contact strip
R_5 = Resistance of diffused region for carriers flowing to grid strip
R_6 = Resistance of bulk region
R_7 = Contact resistance of bulk region to bottom electrode
R_8 = Resistance of bottom electrode

REPRESENTATION OF AN N-UNIT FIELD SOLAR CELL

FIG. 3-1

T-2133

has been developed for the total series resistance of any cell in terms of the component resistances where the current from the diffused layer is collected from one end of the contact strip. This equation is given by:

$$R_{tc} = \frac{R_c}{1+\frac{R_c}{R_p}} + R_1 + R_6 + R_7 + R_8 \quad ; \qquad (3\text{-}3)$$

where:

$$R_c = \frac{\left\{1 + \frac{R_1}{R_3+\frac{1}{2}(R_2+R_5)} + \frac{R_1}{R_1+R_2+R_4}\right\}\left\{R_2 + R_4\right\}}{2 + \frac{R_1 + R_2 + R_4}{R_3+\frac{1}{2}(R_2+R_5)}} \quad ; \qquad (3\text{-}4)$$

$$R_p = \frac{2R_c\ (R_c+R_1)}{(n-1)(2R_c+R_1)} \qquad (3\text{-}5)$$

For the shingled case, where $R_1 = 0$, Eq. (3-3) reduces to:

$$R_{tc} = \frac{R_c}{n} + R_6 + R_7 + R_8 \quad ; \qquad (3\text{-}6)$$

where n is the number of grid lines on the cell. These equations represent the general equation, of which equation (3-13) of the First Quarterly Progress Report is a special case when n=1, and were used to determine theoretically the resistance of typical N^+/P and P^+/N cells.

For the N^+/P cells, the following resistance values (which have been experimentally determined as discussed in the Second Quarterly Progress Report) were used: $R_1 = 0.002$, $R_2 = 0$, $R_3 = 0.4$, $R_4 = 27.0$, $R_5 = 3.8$, $R_6 = 0.25$, $R_7 = 0.08$, and R_8 is effectively zero ohms. When these values are substituted into equations (3-3) through (3-5) the total theoretical series resistance was found to be 0.73 ohms.

Although there is a significant variation in total solar cell series resistance, several random groups (20 cells per group) have been measured, giving rise to the following results for N^+/P cells:

Cell Efficiency	11%	12%	13%
Series Resistance (Ohms)	0.90	0.87	0.74
Standard Deviation	0.39	0.19	0.09

It is extremely interesting to note that the standard deviation decreases rapidly as the cell efficiency increases. That is to say, for example, that an N^+/P cell having a series resistance much larger than 0.83 will probably not have an efficiency of 13% or greater. (It should be mentioned here that the distribution is not Gaussian, being much wider for resistance values greater than the average than for resistance values lower than the average.) This clearly indicates that the series resistance is a strongly limiting factor in the production of high efficiency cells, although, obviously, low series resistance alone will not assure a high efficiency cell.

The results of the experimental measurements are in excellent agreement with the predicted theoretical value of 0.73 ohms, since this is well within the spread of series resistance values for the 13% cells and, in fact, extremely close to the average value experimentally determined. Larger values of series resistance (and lower efficiency cells) result from processing difficulties and could be predicted theoretically by substituting the higher value of the component resistance or resistances involved. For example, if a problem in contact deposition occured, giving rise to a higher contact resistance, this new value would be utilized in the theoretical calculation in place of the value of 0.08 ohm which was used in the previous calculations.

A similar calculation was also done for a P^+/N, production type solar cell, where R_1, R_2, R_3, R_4, R_5, R_6, R_7, and R_8 had the values of .002, 0, 0.4, 16.2, 2.3, 0.02, 0.08, and 0 ohms respectively, and a value of 0.38 ohms was obtained for the total resistance.

For P/N cells having efficiencies of 13 and 14% under 2800°K tungsten

light the series resistance was experimentally found to be 0.43 and 0.42 ohms respectively with no significant standard deviation. (Twenty cells were randomly selected in each efficiency group). This compares quite well with the theoretically predicted value of 0.38 ohms though somewhat less spectacularly than the agreement between the theoretical and experimental values for N^+/P cell series resistance.

CONCLUSIONS

By means of the theoretical equations developed in these reports the total series resistance can be determined from a knowledge of the values of the component resistances. The theoretical prediction for the series resistance of N^+/P cells fabricated from approximately 10 ohm-cm material was 0.73 ohms while the experimentally measured value for high efficiency N^+/P cells was 0.74 ohms. The equations also predicted a total series resistance of 0.38 ohms for P^+/N cells fabricated from approximately 1 ohm-cm material while the experimentally measured value for high efficiency cells of this type was 0.42 ohms. Actually the agreement between the theoretical and experimental values for cell series resistance, even though not comparing as well as in the N/P case, is more representative for the P^+/N cell than for the N^+/P cell. It is more likely that the predicted value will be somewhat lower than the experimental value since minimum values of R_4 and R_5 were used. Also, there is an estimated error of about 5% in the experimental measurement of the series resistance.

The theoretical equations have worked quite well for the two cell types investigated. However, as was pointed out in the First Quarterly Progress Report, these equations will be valid only if the surface of the cell is approximately an equipotential surface, but will be erroneous if the non-linear effects of the junction become appreciable since the equations concern themselves with the passive or linear components of the cell circuit. If the equations are to be used to determine the

optimum grid spacing as indicated in the following equation:

$$I = I_o \left[\exp \frac{q}{AkT} \left(V - IR_{ts}\ (S) \right) - 1 \right] - I_L \quad ; \qquad (3\text{-}7)$$

the surface will most likely be an equipotential for the optimum or near optimum condition, so that the limitation imposed by the omission of the non-linear elements of the equivalent circuit will probably not affect the applicability of the equations. It should be mentioned here that due to the complexity of the equation representing the total resistance (especially in terms of the distance, S, between grid lines) and the fact that I appears not only on the left side of the equation but in the right hand exponential as well, the optimization can be carried through only by means of a computer.

POLYVARIABLE EXPERIMENTS

P^+/N CELLS

The bivariable experiment involving variation of diffusion time and number of grid lines for optimization of P^+/N type solar cells at normal and at concentrated solar intensities in a terrestrial environment was completed during the second report period and evaluated during the third report period.

A convenient way of evaluating the data obtained from the polyvariable experiment would be to plot out the approximate isopower lines, obtained from the results of the experiments, thus representing the surface of a three dimensional figure. The X-Y plane coordinates were represented by the diffusion depth and number of grid lines. The height of the surface was a figure of merit and was equal to the cell output power per milliwatt of input solar intensity.

Several points should be emphasized at this time. First, it is felt that the results of the experiment are quite rewarding in that they show the trend which one would expect to see on a theoretical basis, and that they agree with the results obtained on the prior, univariable experiments. It is very likely then, that the experiment was in excellent control, much better in fact than one would expect owing to the many sources of error inherent in solar cell fabrication. If this degree of control could be carried over to production of solar cells, significant improvement in the yield of high efficiency cells could be made.

The second point is that the isopower curves which are shown in the following figures are strictly qualitative in nature. Experimentally measured points have been used to tie down the curves at one or more places, but the shape of the curve is basically an extrapolation.

Since these curves, as rudimentary as they might be, show clearly the desired information, namely in what direction we should proceed, more elaborate analysis of this data is not required.

It will be remembered that in the polyvariable experiment each cross on the design matrix represented a starting lot of 10 blanks. In order to provide some idea as to the consistancy of the diffusion and to the reproducibility in general, in actuality each cross represented two diffusion runs or groups, one a repeat of the other, of five solar blanks each having the number of grid lines indicated in the abscissa. Several methods of evaluating and ploting the data can be considered. The average power/solar intensity appropriate to each group for each cross are two numbers which are simply the results of two separate runs having the same design parameters. It was decided in plotting the results, to utilize the average P_{max}/solar intensity of both groups comprising each cross as the figure of merit for that cross unless otherwise indicated. The most convenient representation of the X-Y plane was simply the original design matrix.

In Fig. 4-1 the isopower curves are presented for the cells at 100 mW/cm^2 solar intensity. It is clear that the surface is tending towards a peak at the upper right hand quadrant of the figure. It is not clear from the data whether or not the peak has actually been included in this quadrant, or occurs to the upper right beyond the boundaries of the quadrant. However, it is obvious that the optimum design at this solar intensity certainly involves a diffusion time not greater than 30 minutes and a grid configuration of not less than seven grids.

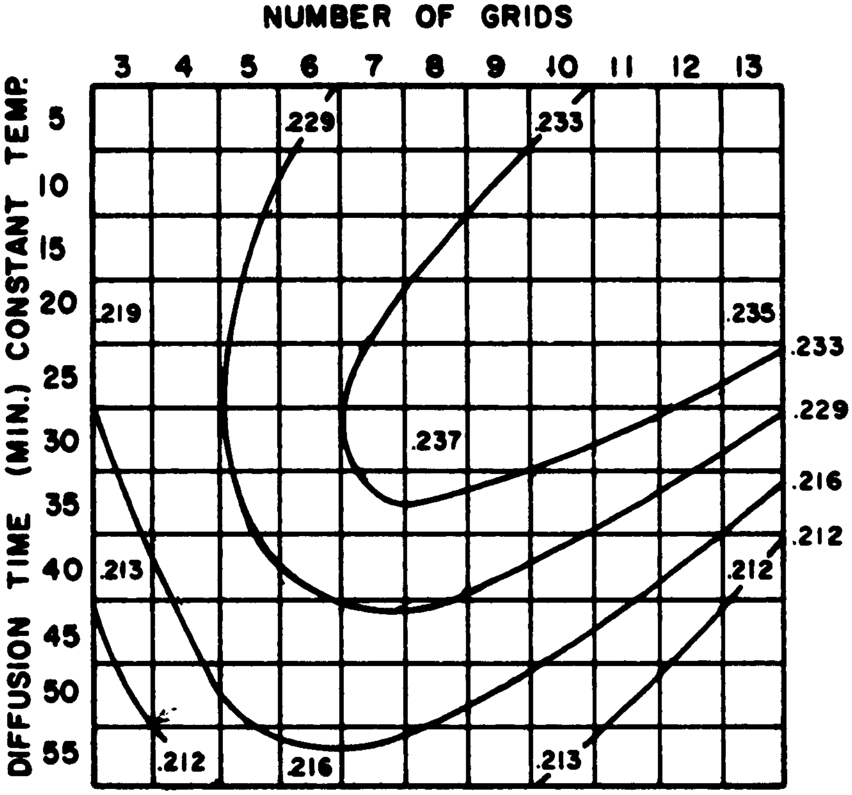
As a matter of interest, the best cells of each of the two groups comprising each cross on the design matrix were averaged (i.e., for each cross there are two values of power/solar intensity which were added and divided by a factor of two.) and the isopower curves are shown in Fig. 4-2.

They show the same general shape as those of Fig. 4-1, but, of course, have higher absolute values. Also, the numerical difference between the average power/solar intensity for the two diffusion groups comprising each cross was obtained and this is shown in Fig. 4-3. Absolute values were used because signs could not be ascribed to either of the two groups. There was no clear pattern indicated. One might expect the largest discrepancies to occur between the groups diffused for five minutes due to the increased processing difficulties involved in the fabrication of shallow diffused cells; however, this was not found to be the case.

The differences between the best cell of each group comprising a cross were also obtained and are shown in Fig. 4-4. It is felt that the poorer cells in any group are due to the processing deviations, and the best cells are relatively free of such process deviations and possibly indicate a more accurate evaluation of the experiment's potential. It was expected that smaller numerical values would be obtained for the difference between the max power/solar intensity of the best cells of each group than for the average cell for each group. However, comparison between Fig. 4-3 and Fig. 4-4 shows that essentially the same pattern exists in either case, indicating that the best cells are simply displaced from the mean by a constant amount. That is, the shape of the distributions (to the extent that one can consider distributions in a five-sample system) for either group are essentially the same but the mean values are displaced from one another.

The average max power/solar intensity at a solar intensity of 163 mW/cm^2 is shown as Fig. 4-5. It can be seen from this figure that the surface continues to rise towards the upper right hand corner. In this case however the highest value actually measured is no longer at the 30 minute diffusion - 8 grid line intersection, but shifted further up to the upper right corner at the 20 minute diffusion - 13 grid line intersection, and also at the five minute diffusion - 10 grid line intersection. The fact

MATRIX REPRESENTATION OF POLYVARIABLE EXPERIMENT FOR P^+/N CELLS

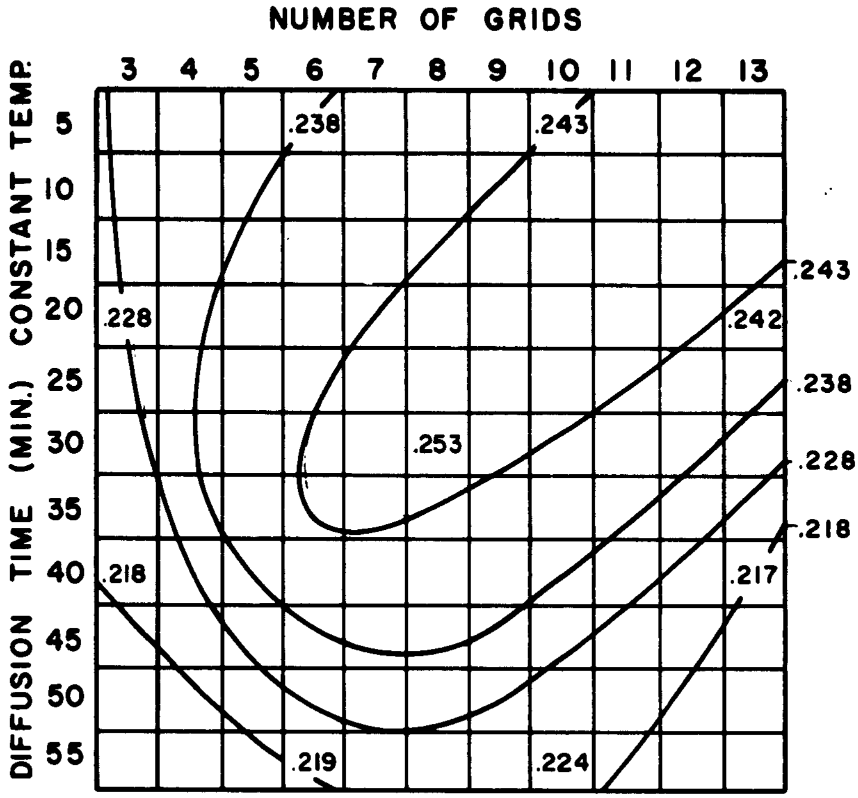


AVERAGE POWER (mW)/SOLAR INTENSITY @ 100 mW/cm^2

FIG. 4-1

T-2128

MATRIX REPRESENTATION OF POLYVARIABLE EXPERIMENT FOR P^{+}/N CELLS



BEST CELL POWER (mW)/SOLAR INTENSITY @ 100mW/cm^2

FIG. 4-2

T-2130

MATRIX REPRESENTATION OF POLYVARIABLE EXPERIMENT FOR P^+/N CELLS

NUMBER OF GRIDS

DIFFUSION TIME (MIN.) CONSTANT TEMP.	3	4	5	6	7	8	9	10	11	12	13
5				.013				.023			
10											
15											
20	.041										.003
25											
30						.007					
35											
40	.001										.006
45											
50											
55				.017				.007			

DIFFERENCE BETWEEN GROUPS
(ABSOLUTE VALUES IN mW @ 100mW/cm^2

FIG. 4-3

MATRIX REPRESENTATION OF POLYVARIABLE EXPERIMENT FOR P^+/N CELLS

NUMBER OF GRIDS

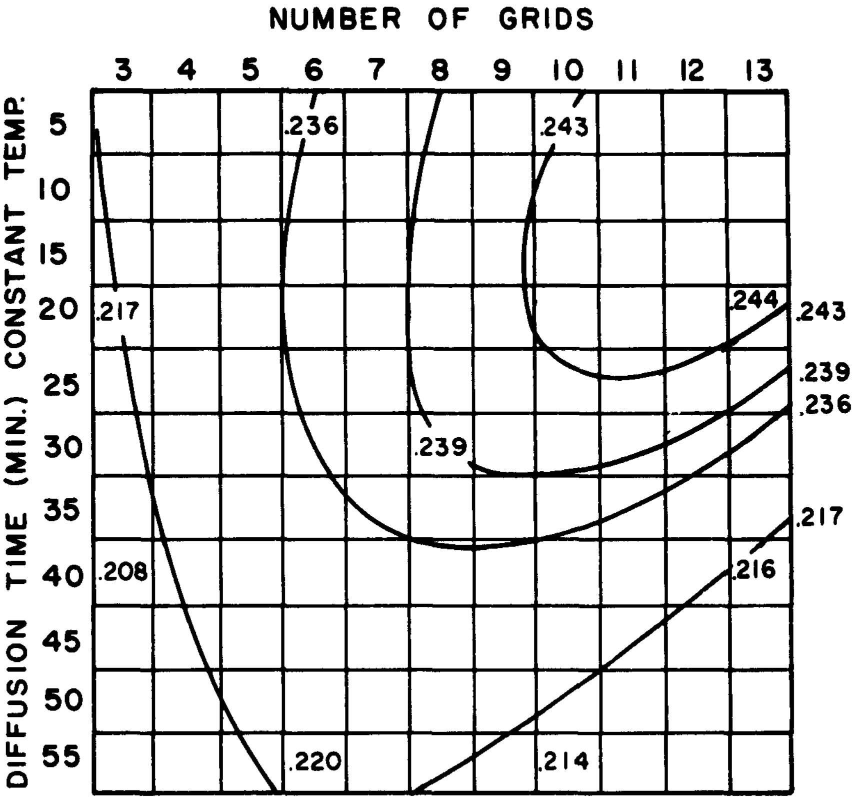
DIFFUSION TIME (MIN.) CONSTANT TEMP.	3	4	5	6	7	8	9	10	11	12	13
5				.019				.024			
10											
15											
20	.035										.003
25											
30						.005					
35											
40	.000										.008
45											
50											
55				.015				.011			

DIFFERENCE BETWEEN BEST CELL GROUPS I AND II

(ABSOLUTE VALUE IN mW)

FIG. 4-4

MATRIX REPRESENTATION OF POLYVARIABLE EXPERIMENT FOR P^+/N CELLS

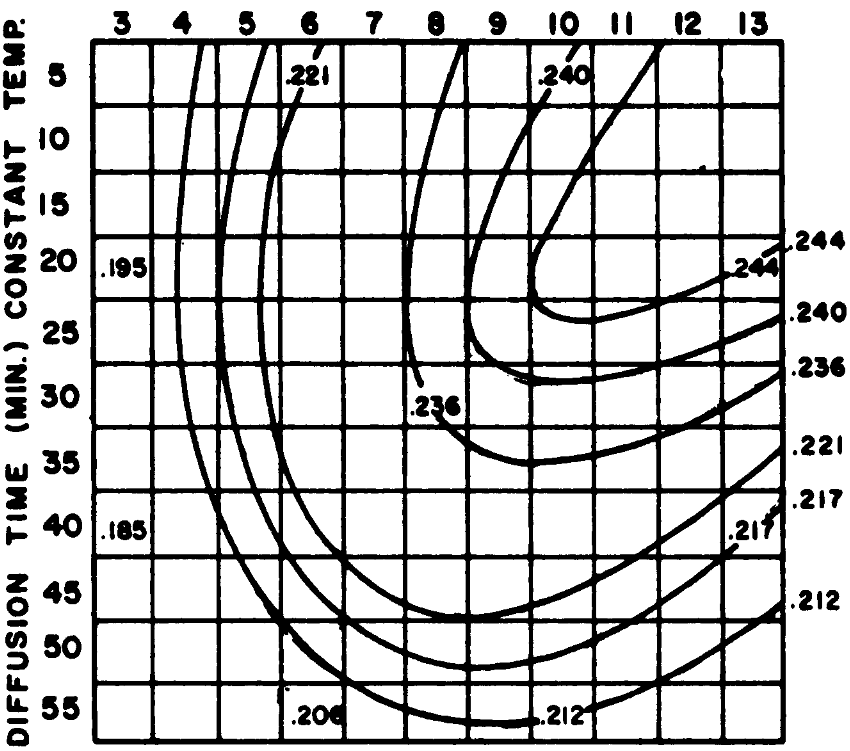


AVERAGE POWER (mW)/SOLAR INTENSITY @ 163 mW/cm²

FIG. 4-5

T-2132

MATRIX REPRESENTATION OF POLYVARIABLE EXPERIMENT FOR P^+/N CELLS



AVERAGE POWER (mW)/SOLAR INTENSITY @ 316 mW/cm²

FIG. 4-6

T-2129

that these latter two design points lie essentially on the same isopower curve is indicative of the fact that there are two ways to achieve the same end, namely sacrifice of blue spectral response in order to achieve low series resistance or sacrifice of low series resistance to achieve favorable spectral response. The increase in the height of the surface towards the upper right-hand corner of the matrix shows the need to mutually optimize these parameters to achieve optimization of the cell design.

The isopower curves of the average max power/solar intensity at an intensity of 316 mW/cm^2 are shown in Fig. 4-6. The surface is still rising towards the upper right-hand corner of the matrix. At this intensity the 20 minute diffused - 13 gridded cells show clear superiority over the 5 minute diffused - 10 gridded cells. (It will be remembered that at a solar intensity of 163 mW/cm^2 the efficiencies of both cell types were almost identical.) This indicates that at this intensity the cell series resistance is becoming a more overriding parameter than at the lower intensities. It is interesting to note that all the max power/solar intensity values which were actually measured have decreased from the values obtained under the 163 and 100 mW/cm^2 solar intensities, except for the 20 minute diffused - 13 line cell group. It is also interesting to note that, according to the isopower curves, a 20 minute diffused - 5 line cell will have higher efficiency than a 10 minute diffused - 5 line cell. It will be remembered that this is precisely what was found in the preliminary investigative type experiments discussed in the First and Second Quarterly Progress Reports.

This last fact serves to illustrate the usefulness of the polyvariable experiment with respect to optimization of device design. If one were simply to proceed by holding the number of grid lines constant at 5 and varying the diffusion time, one would find indeed that the optimum diffusion time is approximately twenty minutes. However, through mere inspection of Fig. 4-6 we see immediately how much more is to be gained

by increasing the number of grid lines. Moreover the mutual optimization of these parameters is graphically indicated.

The next step, of course, is to conduct another such experiment which is much more selective with emphasis on the upper right hand quadrent in order to provide more data points in this region and consequently more exact optimization. It is expected that the addition of more grid lines (beyond the 13 which were investigated here) will eventually lead to a surface which is slowly decreasing due to the attenuation of usable light by the grid lines and a consequent decrease in cell current which cannot be compensated for by further decrease of the series resistance. (It will be remembered that in the First Quarterly Progress Report, utilization of Wolf's[1)] equation for grid optimization of a P^+/N cell gave rise to a nine line grid pattern for a P^+/N cell having a sheet resistance of about 40 ohms and an A factor value of 2.) An entirely different result is expected through further decrease of the diffusion time however, namely a catastrophically downward slope of the surface due to extremely poor junction formation arising out of the very strong dependence of shallow junctions on surface conditions (especially non-uniformities such as strains, imperfections, dislocations, etc.) and on the transient diffusion conditions. (For deeper diffusions the diffusion process reaches a steady state condition.)

1) M. Wolf, "Limitations and Possibilities for Improvement of Photovoltaic Solar Energy Converters, Considerations for Earth's Surface Operation" Proc. IRE, July, 1960.

DESIGN OF PILOT LINE FOR 500 P^+/N CELLS

The type of cell design which is not desirable is quite clear from the experiments; however, due to the small number of experimental points in the region of increasing surface height, the exact location of the surface maximum is unknown. It has been decided, based on the contour plots, to utilize a fifteen minute diffusion time and an eleven line grid pattern. According to the isopower curves at 316 mW/cm^2, cell parameters which look equally promising are as follows: (with diffusion time listed first and number of grid lines listed second) 15 min - 12, 15 min - 13, 20 min - 11, 10 min - 12, 10 min - 13, 5 min - 12, 5 min - 13. Diffusion times of 10 minutes or less were eliminated simply because it is felt that a better yield can be obtained from cells having a somewhat deeper junction. The twenty minute diffused cell was not used because it was felt that too much blue response might be sacrificed. The twelve and thirteen line grids were not utilized because it was felt that there might be too great a current loss due to the area covered by the grid lines.

N^+/P CELLS

The fabrication of the N^+/P cells for the polyvariable experiment was carried through in much the same manner as the previous experiment with the P^+/N cells. The design matrix is shown in Fig. 4-7. Each cross on the design matrix represents three diffusion groups of five cells having the diffusion times and number of grid lines indicated. Unfortunately, the third 40 minute diffusion group of cells were lost to the experiment due to processing difficulties.

The same method of evaluation was utilized as had been used in the previous polyvariable experiment. The cells were measured in a tungsten light system having a color temperature of 2800°K and were maintained at a cell temperature of 28°C ± 2°C by means of a water-cooled block. The short circuit current of each cell was also measured in natural sunlight at Table Mountain, California at a solar intensity of approximately 100 milliwatts per square centimeter, and the multiplicative constant which is utilized in the prediction of the power in sunlight as predicted from the power measured in tungsten light was determined from the following relationship:

$$C = \frac{I_{sc}\ (\text{Sun at } 100\ \text{mW/cm}^2)}{I_{sc}\ (\text{Tungsten at } 100\ \text{mW/cm}^2)} \quad ; \qquad (4\text{-}1)$$

where C is the multiplicative constant and the denominator is the short circuit current as measured in the tungsten system which has been calibrated to correspond to a solar intensity of 100 milliwatts per square centimeter.

The values of the multiplicative constant which were obtained were quite unexpected. So much so, in fact, that the cells were remeasured in both the tungsten system and in sunlight at Table Mountain, California to verify the results obtained. Instead of obtaining numerical values of C which decreased with increasing diffusion time as would be expected

MATRIX REPRESENTATION OF POLYVARIABLE EXPERIMENT FOR N^{+}/P CELLS

NUMBER OF GRIDS

DIFFUSION TIME (MIN.) CONSTANT TEMP.	3	4	5	6	7	8	9	10	11	12	13
10				X				X			
20											
30											
40	X										X
50											
60						XX					
70											
80	X										X
90											
100											
110				X				X			

FIG. 4-7

and as was observed in the P^+/N experiment, the values of C decreased only occasionally for certain cell groups, but for the most part remained quite high. That is to say, the 10 minute diffused cells had a value of C which was identical to the C values of cells diffused for 110 minutes and in some cases the 10 minute cells had a lower value! It has usually been found that the blue response of a cell decreases rapidly with increasing diffusion depth so that the red to blue response ratio of a deep diffused cell is higher than for a shallow-diffused cell. Thus, the deep diffused cell is less blue-sensitive and has a smaller multiplicative constant, C. This did not seem to be the case for these cells. In order to further understand the reason for the unexpected results, spectral responses were obtained. The responses more or less verified the results of the multiplicative factor calculations. There was little significant difference between most of the spectral responses regardless of the cell diffusion time. In fact, some of the deeper diffused cells showed better blue response, both on a relative and absolute comparative basis, than the shallow, ten minute diffused cells!

If the results of this experiment are valid, the indication is that the spectral response of N^+/P cells is not nearly as sensitive to junction depth as the spectral response of P^+/N cells. This could be the case if, for example, the minority carrier diffusion length of the diffused region of the N^+/P cell is greater than a micron, so that carrier collection from the diffused region is more efficient than for a P^+/N cell, and will remain efficient for junction depths up to about a micron. It might be expected that less severe recombination centers should exist in phosphorous doped silicon than in boron doped silicon, since phosphorous is a much better match for the silicon lattice than boron and would therefore result in a less violent disruption of the periodicity of the silicon lattice.

During the developmental program on N^+/P solar cells it was observed

that the tungsten-sunlight multiplicative factor varied between 0.86 and 1.01 as the silicon monoxide, antireflectance coatings varied from a light blue to a rather dark blue, all other cell parameters having been maintained constant.

It might therefore be considered that variations in the optical antireflectance coatings (especially in view of the fairly rough surface of the cell) could have a greater effect on the cell spectral response, and consequently the multiplicative factor C, than the variation of junction depth through diffusion time.

Evaluation of the N^+/P polyvariable experiment was done in the same manner as for the previous P^+/N experiment. The data showing the average maximum power output per unit solar intensity for each cell group at intensities of 100, 163, and 316 milliwatts per square centimeter is presented in Table IV-1. The value for the best cell of the group is presented directly below the average value and is denoted by an asterisk. Column I identifies the group, showing the diffusion run number, the number of grid lines, and the diffusion time. Columns II, IV and VI show the average maximum power of each group of cells corrected to correspond to sunlight intensities of 100, 163, and 316 milliwatts per square centimeter respectively. Columns III, V, and VII show the average maximum power per unit solar intensity for each cell group at the 100, 163, and 316 milliwatt per square centimeter intensities. These results are shown graphically in Figs. 4-8 through 4-13.

From the information obtained in Table IV-1 the isopower curves were drawn onto the design matrix and these curves are shown in Figs. 4-14 through 4-16 for the 100, 163, and 316 milliwatt per square centimeter intensities. It can immediately be seen from these curves that the shape of the surface is considerably different from that which was obtained in the P^+/N bivariable experiment. In the latter case, the surface rose towards the upper right hand quadrant of the design matrix.

TABLE IV-1

RESULTS OF N^+/P BIVARIABLE EXPERIMENTS

*Represents Best Cell of the Group

I	II	III	IV	V	VI	VII
	Ave. Corrected Max. Power (mW) at 100 mW	P_{max} per mW/cm^2 solar Int. at 100 mW	Ave. Corrected Max. Power (mW) at 163 mW	P_{max} per mW/cm^2 solar Int. at 163 mW	Ave. Corrected Max. Power (mW) at 316 mW	P_{max} per mW/cm^2 solar Int. at 316 mW
1097 6 grid (110 min)	19.9 22.1*	.199 .221*	33.6 36.8*	.206 .225*	63.0 68.0*	.199 .215*
1097 10 grid (110 min)	17.9 20.0*	.179 .200*	31.0 34.6*	.190 .212*	60.0 67.0*	.189 .212*
1102 6 grid (110 min)	21.8 22.0*	.218 .220*	35.9 36.4*	.220 .223*	66.0 67.0*	.208 .212*
1102 10 grid (110 min)	21.6 22.5*	.216 .225*	35.8 36.5*	.219 .223*	68.0 68.0*	.215 .215*
1104 6 grid (110 min)	23.2 23.5*	.232 .235*	37.9 38.4*	.232 .235*	70.0 71.0*	.221 .224*
1104 10 grid (110 min)	22.1 22.4*	.221 .224*	37.2 37.7*	.228 .231	70.0 71.0*	.221 .224*
1099 3 grid (80 min)	21.1 22.6*	.211 .226*	33.2 35.3*	.203 .216*	57.0 57.0*	.180 .180*
1099 13 grid (80 min)	20.9 21.6*	.209 .216*	34.7 35.4*	.212 .217*	66.0 69.0*	.208 .218*
1105 3 grid (80 min)	21.8 22.3*	.218 .223*	33.8 34.7*	.207 .212*	57.0 57.0	.180 .180*

TABLE IV-1 (Cont.)

I	II	III	IV	V	VI	VII
1105 13 grid (80 min)	23.6 25.0*	.236 .250*	39.9 41.8*	.244 .256*	69.0 73.0*	.218 .231*
1107 13 grid (80 min)	22.1 22.7*	.221 .227*	36.8 38.1*	.225 .233*	69.0 69.0*	.218 .218*
1107 3 grid (80 min)	22.5 23.0*	.225 .230*	35.0 35.2*	.214 .216*	57.0 57.0*	.180 .180*
1101 8 grid (60 min)	19.7 20.9*	.197 .209*	32.9 34.7*	.201 .212*	63.0 65.0*	.199 .205*
1109 8 grid (60 min)	22.5 23.7*	.225 .237*	37.2 39.1*	.228 .239*	70.0 73.0*	.221 .231*
1110 8 grid (60 min)	21.8 22.5*	.218 .225*	36.2 37.0*	.222 .226*	68.0 70.0*	.215 .221*
1100 3 grid (40 min)	19.9 21.1*	.199 .211*	31.5 32.6*	.193 .200*	52.0 52.0*	.164 .164*
1100 13 grid (40 min)	18.9 21.4*	.189 .214*	32.8 35.2*	.201 .215*	63.0 66.0*	.199 .208*
1111 3 grid (40 min)	21.5 21.9*	.215 .219*	32.8 33.5*	.201 .205*	52.0 53.0*	.164 .167*
1111 13 grid (40 min)	22.1 22.4*	.221 .224*	37.3 37.7*	.228 .231*	71.0 71.0*	.224 .224*
1098 6 grid (10 min)	16.9 18.5*	.169 .185*	28.5 30.7*	.174 .188*	52.0 55.0*	.164 .174*

TABLE IV-1 (Cont.)

I	II	III	IV	V	VI	VII
1098 10 grid (10 min)	16.1 19.5*	.161 .195*	28.0 34.0*	.171 .208*	57.0 65.0*	.180 .205*
1103 6 grid (10 min)	19.3 20.2*	.193 .202*	31.8 32.3*	.195 .198*	54.0 55.0*	.170 .174*
1103 10 grid (10 min)	19.3 19.6*	.193 .196*	32.1 34.3*	.196 .210*	63.0 65.0*	.199 .205*
1106 6 grid (10 min)	19.8 20.7*	.198 .207*	33.4 34.7*	.204 .212*	60.0 62.0*	.189 .196*
1106 10 grid (10 min)	19.2 20.9*	.192 .209*	32.7 34.3*	.200 .210*	64.0 66.0*	.202 .208*

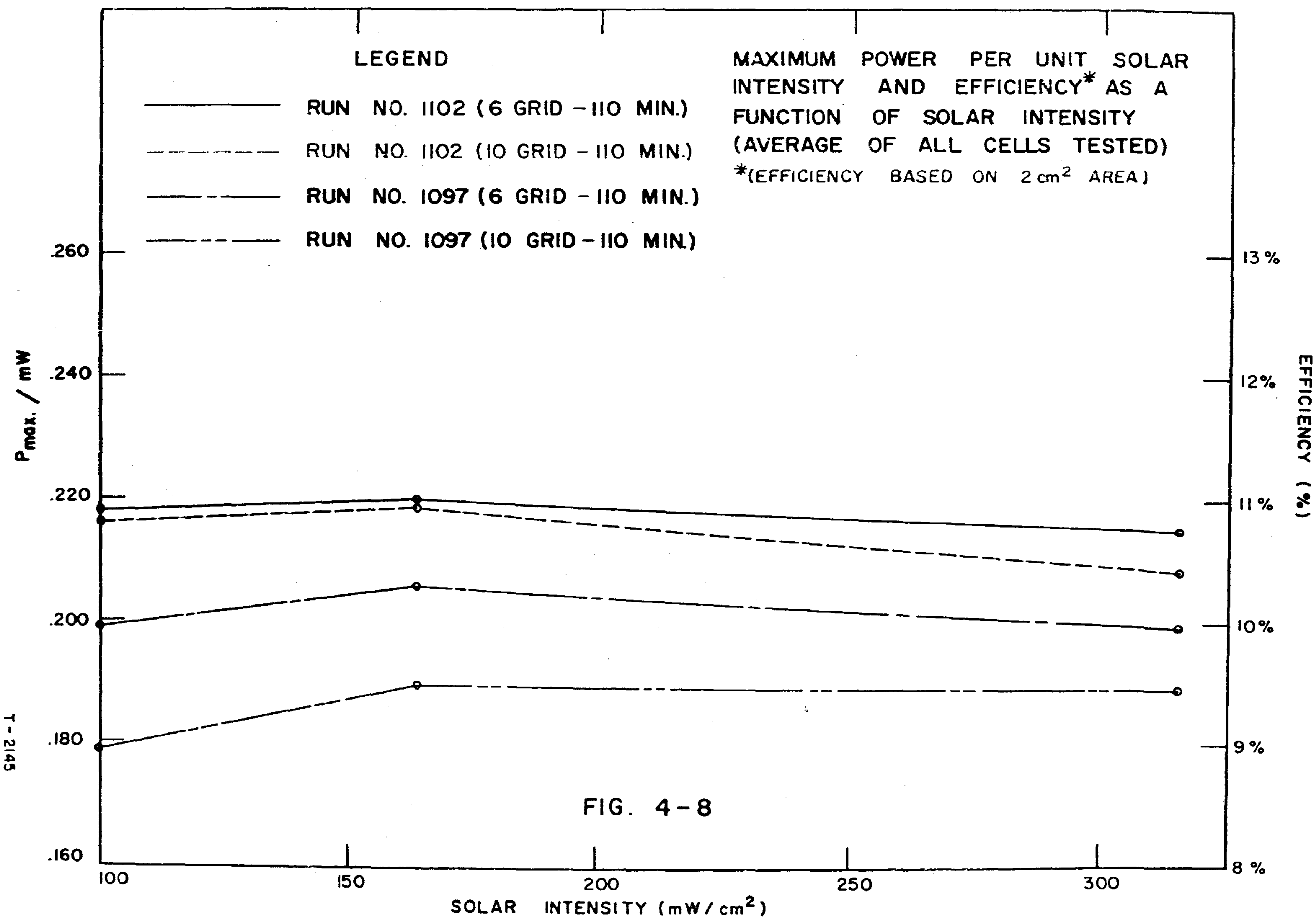

LEGEND
RUN NO. 1102 (6 GRID – 110 MIN.)
RUN NO. 1102 (10 GRID – 110 MIN.)
RUN NO. 1097 (6 GRID – 110 MIN.)
RUN NO. 1097 (10 GRID – 110 MIN.)
MAXIMUM POWER PER UNIT SOLAR INTENSITY AND EFFICIENCY* AS A FUNCTION OF SOLAR INTENSITY (AVERAGE OF ALL CELLS TESTED)
*(EFFICIENCY BASED ON 2 cm² AREA)
.260
.240
.220
.200
.180
.160
Pmax. / mW
13 %
12%
11 %
10%
9 %
8 %
EFFICIENCY (%)
100
150
200
250
300
SOLAR INTENSITY (mW / cm²)

FIG. 4-8

T-2145

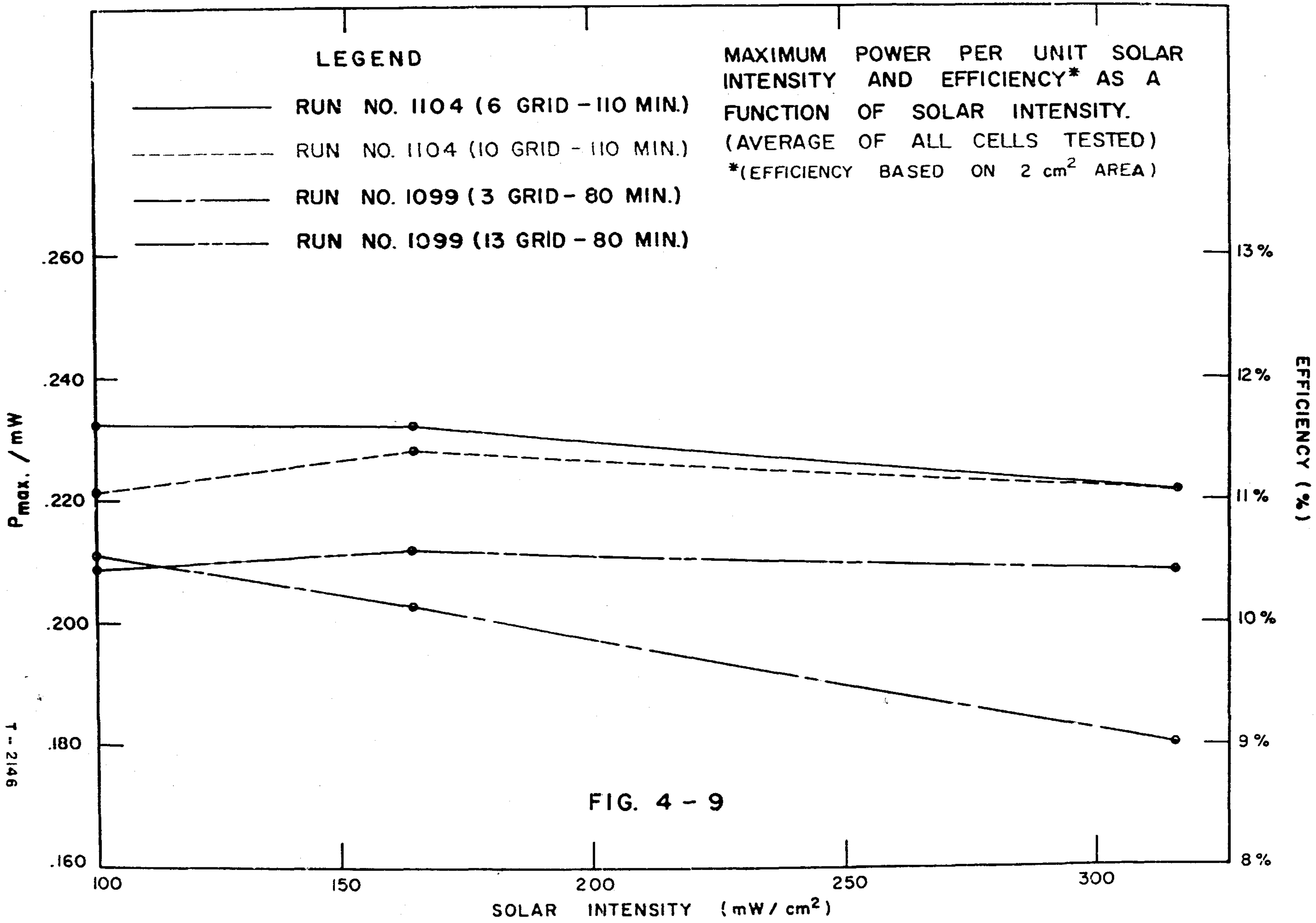

LEGEND
RUN NO. 1104 (6 GRID - 110 MIN.)
RUN NO. 1104 (10 GRID - 110 MIN.)
RUN NO. 1099 (3 GRID - 80 MIN.)
RUN NO. 1099 (13 GRID - 80 MIN.)
MAXIMUM POWER PER UNIT SOLAR INTENSITY AND EFFICIENCY* AS A FUNCTION OF SOLAR INTENSITY.
(AVERAGE OF ALL CELLS TESTED)
*(EFFICIENCY BASED ON 2 cm² AREA)
.260
.240
.220
.200
.180
.160
P max. / mW
13%
12%
11%
10%
9%
8%
EFFICIENCY (%)
100
150
200
250
300
SOLAR INTENSITY (mW / cm²)

FIG. 4 - 9

T - 2146

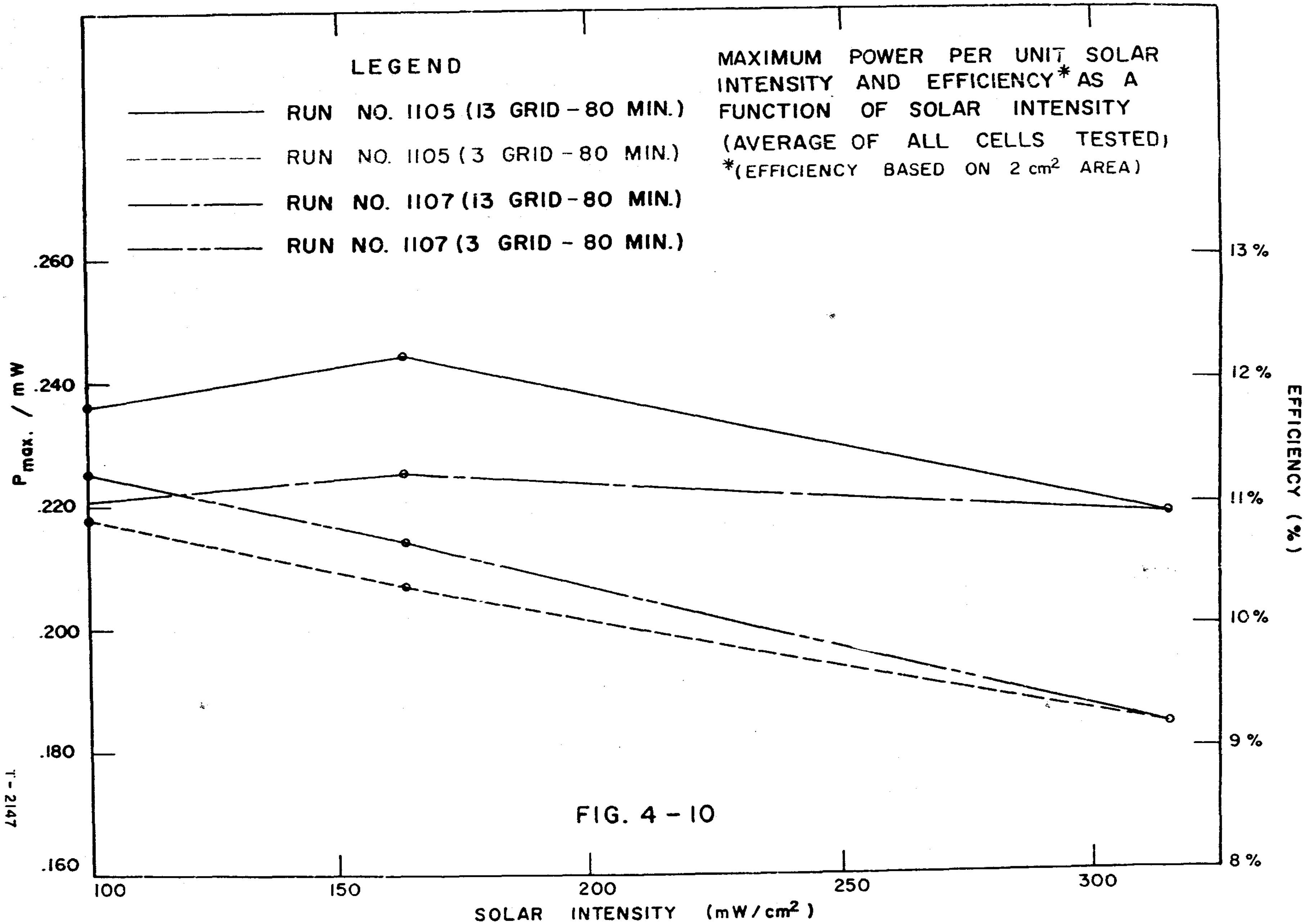


FIG. 4 - 10

T-2147

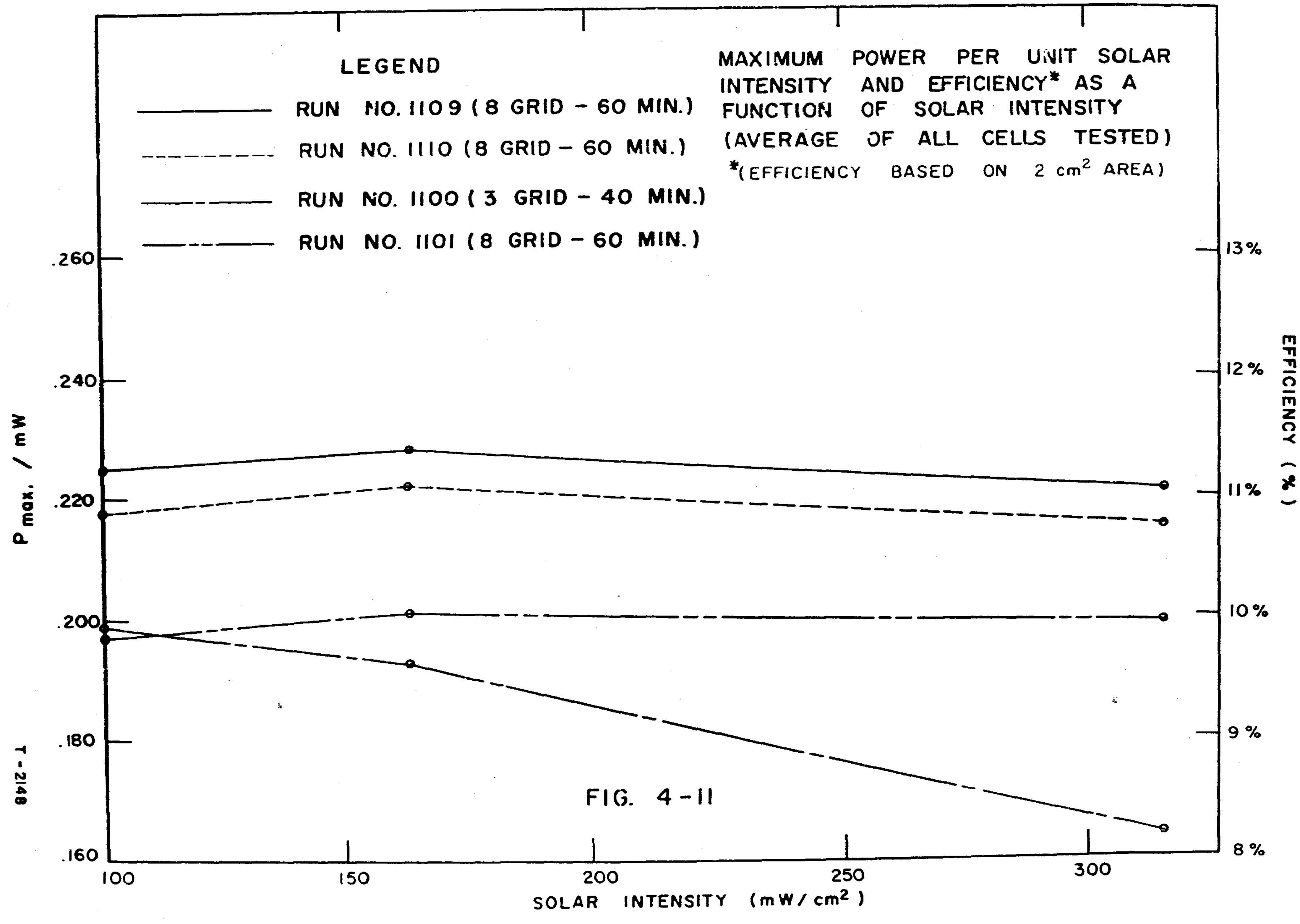


FIG. 4-11

T-2148

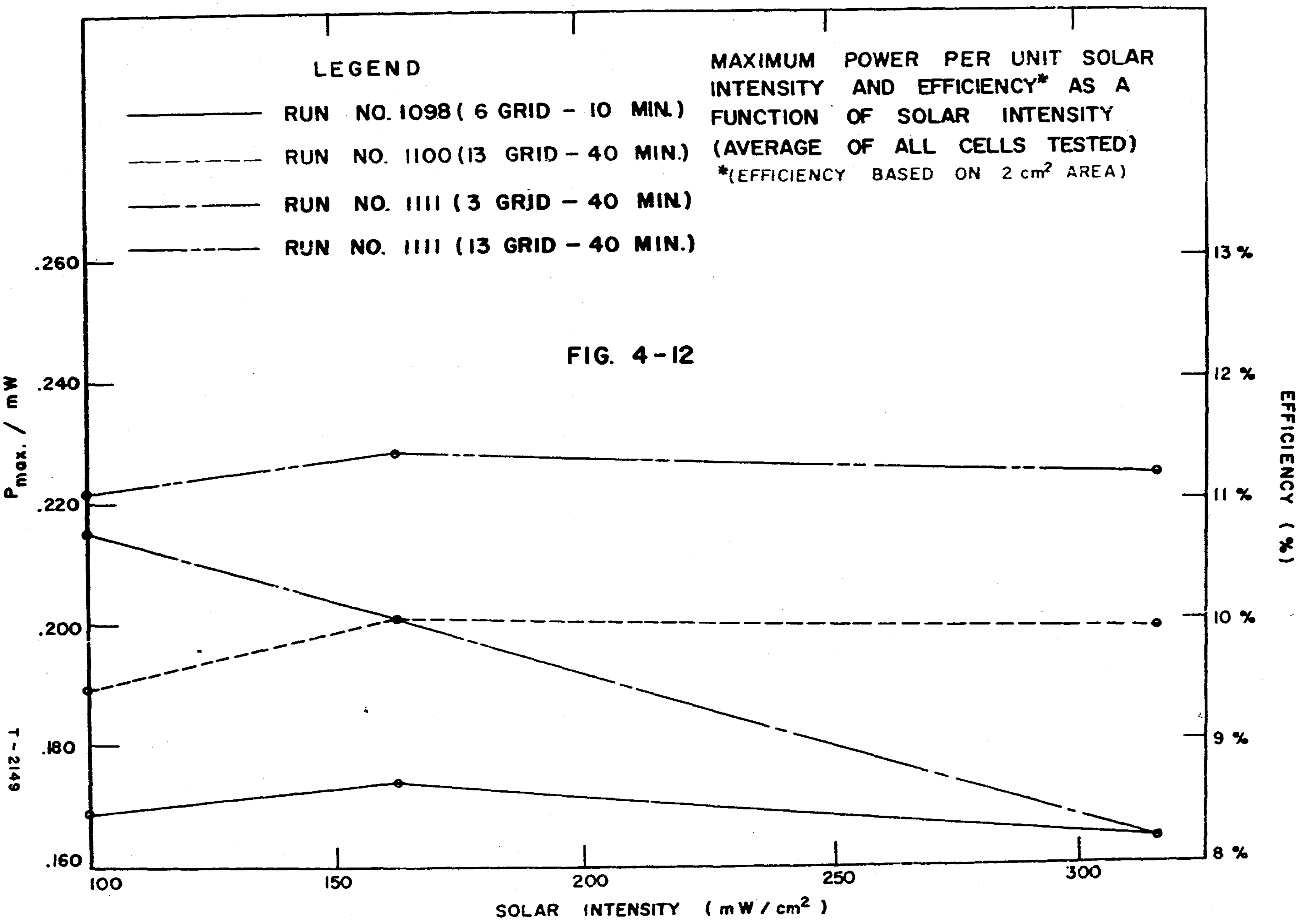


FIG. 4-12

T - 2149

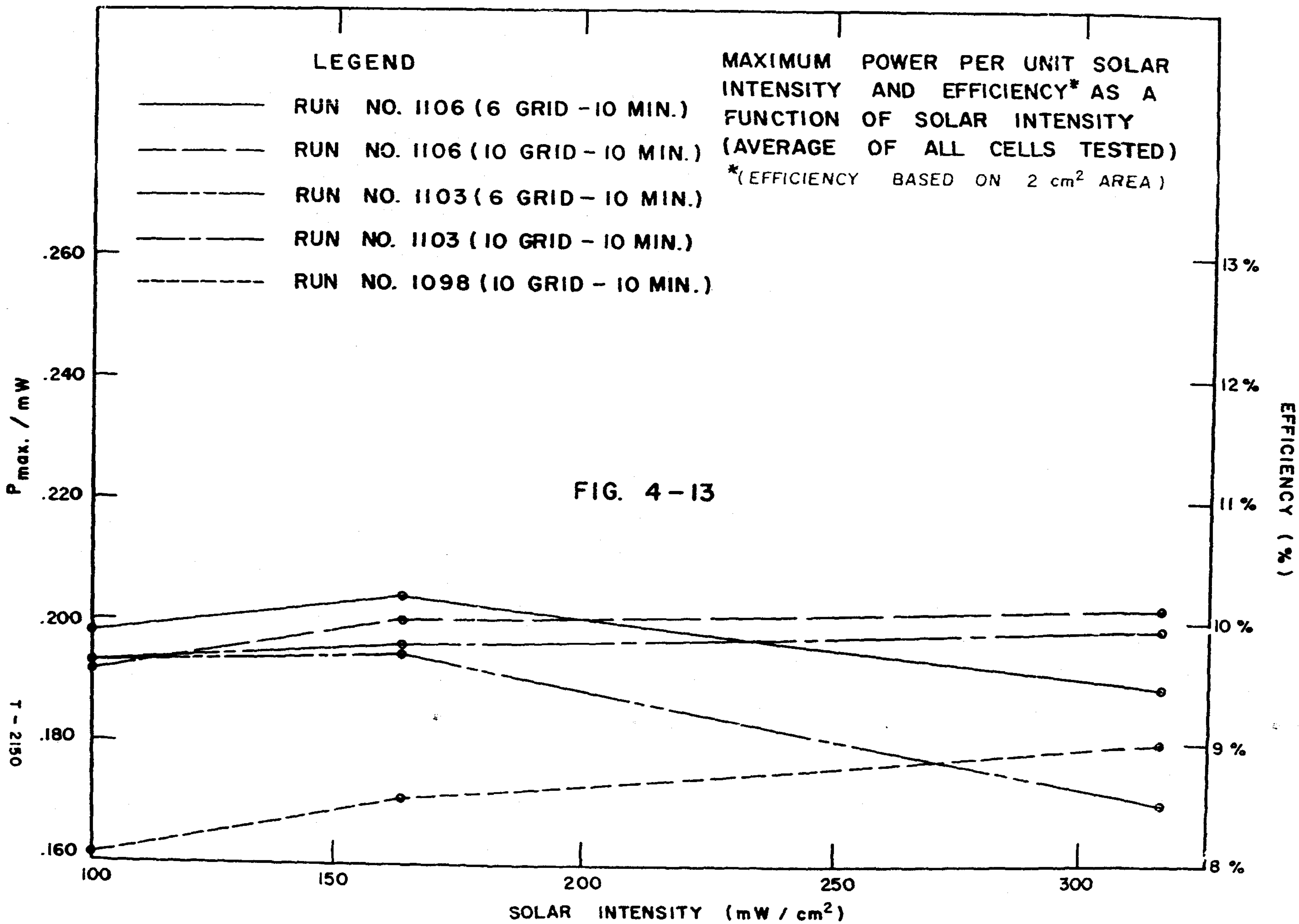
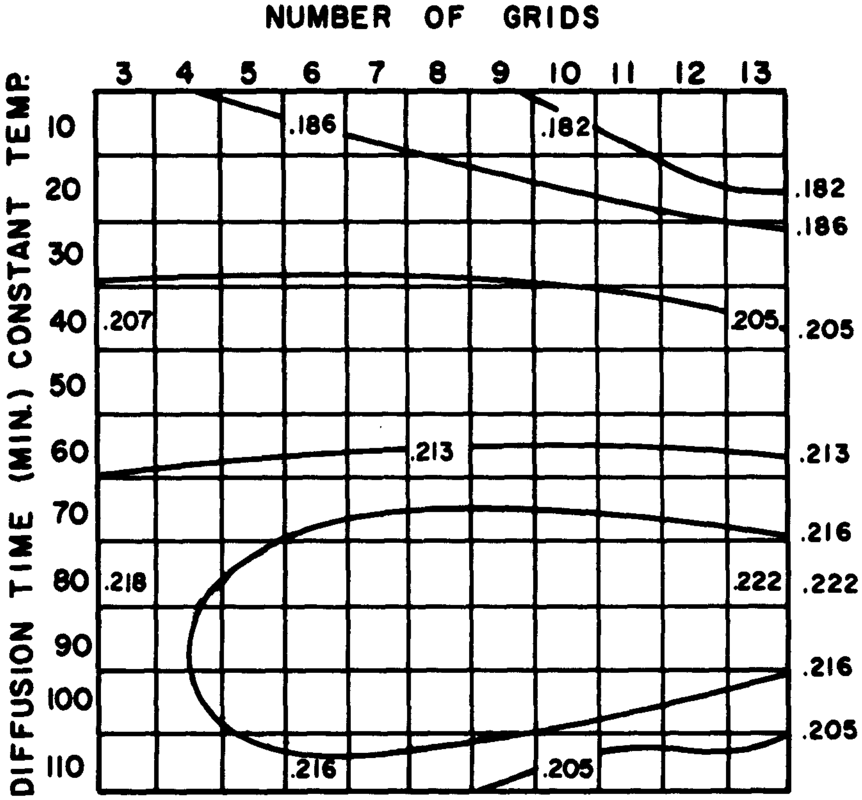

LEGEND
RUN NO. 1106 (6 GRID - 10 MIN.)
RUN NO. 1106 (10 GRID - 10 MIN.)
RUN NO. 1103 (6 GRID - 10 MIN.)
RUN NO. 1103 (10 GRID - 10 MIN.)
RUN NO. 1098 (10 GRID - 10 MIN.)
MAXIMUM POWER PER UNIT SOLAR INTENSITY AND EFFICIENCY* AS A FUNCTION OF SOLAR INTENSITY (AVERAGE OF ALL CELLS TESTED)
*(EFFICIENCY BASED ON 2 cm² AREA)
P max. / mW
.260
.240
.220
.200
.180
.160
100
150
200
250
300
SOLAR INTENSITY (mW / cm²)
EFFICIENCY (%)
13 %
12 %
11 %
10 %
9 %
8 %

FIG. 4-13

MATRIX REPRESENTATION OF POLYVARIABLE EXPERIMENT FOR N^+/P CELLS

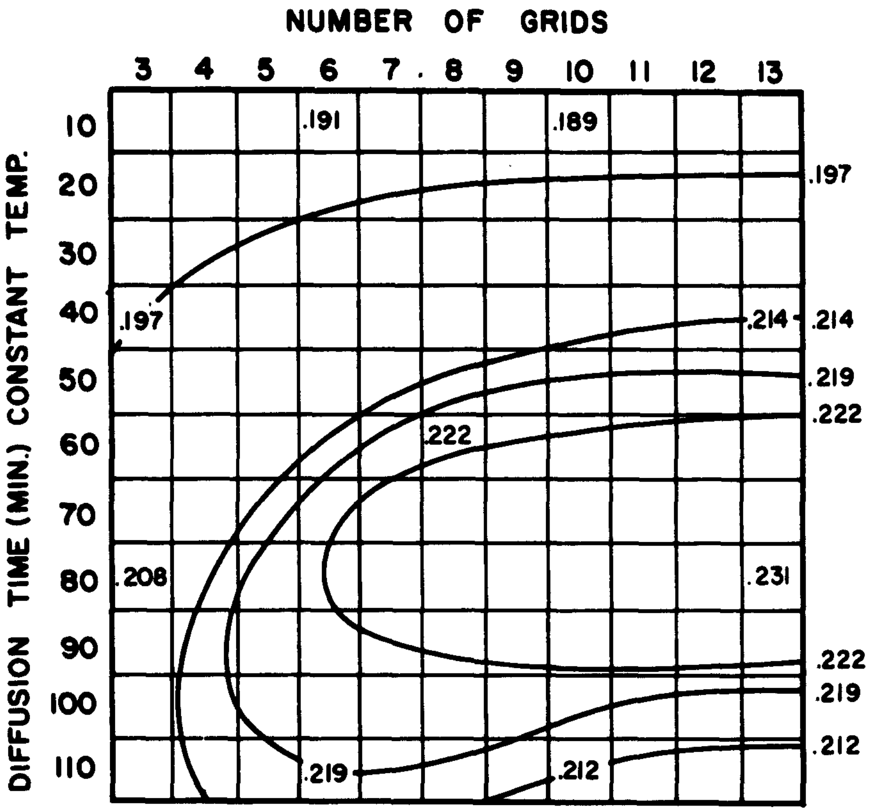


AVERAGE POWER (mW)/SOLAR INTENSITY @ 100mW/cm²

FIG. 4-14

T-2137

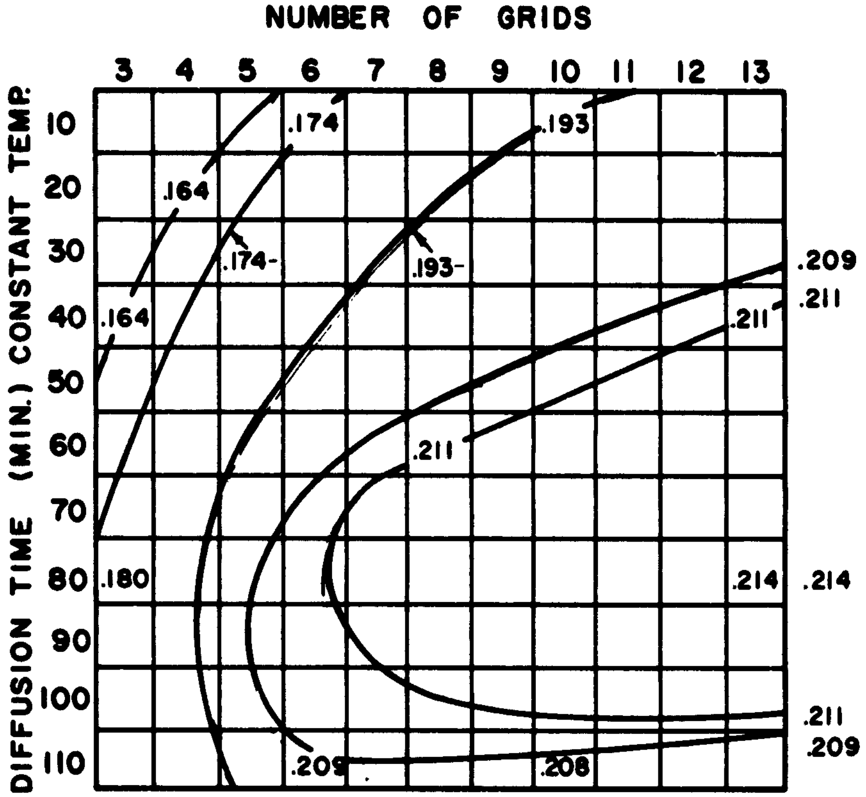
MATRIX REPRESENTATION OF POLYVARIABLE EXPERIMENT FOR N^+/P CELLS



AVERAGE POWER (mW) / SOLAR INTENSITY @ 163 mW/cm²

FIG. 4-15

MATRIX REPRESENTATION OF POLYVARIABLE EXPERIMENT FOR N⁺/P CELLS



AVERAGE POWER (mW) / SOLAR INTENSITY @ 316mW/cm²

FIG. 4-16

T-2136

In this case, however, the surface tends towards a maximum in the lower right hand quadrant of the design matrix. Again, as in the case of the P^+/N experiment the actual optimum has not been clearly defined. Hence, we are left with a number of choices for the final cell design, within the optimum region of the matrix. In this case, the 80 minute diffusion time was chosen because at all three intensities the peak of the contour plot appeared at this diffusion time and the highest max power/unit intensity actually measured occurred at this position. The eleven-line grid pattern was decided upon since it seemed well within the highest isopower curve, although grid patterns having 9 through 13 lines could also be used. Thus, the cell design which will be utilized in the fabrication of the 500 N^+/P cells consists of an 80 minute diffusion and an eleven-line grid configuration.

COST FACTORS

During this report period several varieties of N^+/P type polycrystalline cells have been fabricated from material having resistivities in the ten ohm centimeter range. Cells diffused for twenty minutes were fabricated with five and ten line grid patterns, and with and without silicon monoxide antireflectance coatings. Also, cells diffused for forty-five minutes were fabricated with five and ten line grid patterns. About five cells were fabricated for each cell type (that is diffusion time, grid pattern, and coating) so that the average values obtained are subject to process variations. The condensed results of the experiment are shown in Table V-1. Column I shows the diffusion time, number of grid lines, and whether or not a silicon monoxide coating was applied. Columns II, III, and IV show the average short circuit current, open circuit voltage, and power as measured in tungsten light (2800° K) respectively. Column V shows the multiplicative constant determined from the ratio of the cell short circuit current as measured in sunlight on Table Mountain at m = 1 (solar intensity of 100 milliwatts per square centimeter) to the short circuit current as measured in the tungsten system which has been calibrated by a standard cell to a solar equivalent intensity of 100 milliwatts per square centimeter. This multiplicative constant is utilized in conjunction with the power output in the calibrated tungsten system to predict the power in natural sunlight. Normally this factor is less than 1.0 and is called a "degradation factor". However in the case of polycrystalline cells, this figure is greater than one due to the higher blue to red response ratio of these type of cells as compared to the single crystalline cells which are used to calibrate the tungsten light system. In the last report the results of low resistivity P^+/N cells showed degradation figures of about 1.3. At that time it was predicted that due to the higher red response of the high resistivity N^+/P polycrystalline cells, the multiplicative constant would not have as large a value as the P^+/N cells which had been tested at that time. This indeed seems to be the case.

TABLE V - I

N^{+}/P POLYCRYSTALLINE CELLS

Third Report Period

I	II	III	IV	V	VI	VII	VIII
	I_{sc} (Avg) (mA)	V_{oc} (Avg) (Volts)	P_{max} (Avg) (mW)	$\frac{I_{sc}\,(Sun)}{I_{sc}\,(Tung)}$	Corrected P_{max} (Avg) (mW) at 100mW Sun Int.	Total Area Sun Eff. (%)	Active Area Sun Eff. (%)
Diff.-20 Min. 5 Grid SiO	44.5	.492	15.2	1.06	16.2	8.1	9.0
Diff.-20 Min. 5 Grid No SiO	43.1	.482	13.1	1.13	14.9	7.4	8.3
Diff.-20 Min. 10 Grid SiO	42.4	.493	14.6	1.11	16.3	8.1	9.1
Diff.-20 Min. 10 Grid No SiO	41.4	.474	12.4	1.11	13.7	6.8	7.6
Diff.-45 Min. 5 Grid No SiO	41.2	.456	11.2	1.14	12.8	6.4	7.1
Diff.-45 Min. 10 Grid No SiO	40.9	.471	12.4	1.14	14.3	7.1	7.9

Column VI shows the average maximum power corrected to correspond to 100 milliwatts per square centimeter solar intensity (the product of columns IV and V).

The highest tungsten short circuit current observed was for the twenty minute-diffused, five line gridded, coated cells. However, the multiplicative constant is somewhat lower than the other cells so that the highest short circuit current in sunlight is obtained from the twenty-minute-diffused, five line, uncoated cell group. This indicates that the coating is not optimized to the cell response, and is probably reflecting far too much of the blue region of the spectrum. The highest open circuit voltage was obtained from the twenty minute diffused, ten gridded cell with a coating applied. The same cell type, except for the fact that they were not coated, showed the lowest open circuit voltage of all the twenty minute-diffused cells. Since the coating should have almost no effect on the open circuit voltage, processing variations seem to be masking any effects caused by the variation of grid lines on resultant cell voltage. The highest power output at 100 milliwatts per square centimeter solar intensity was obtained from the twenty minute diffused cells with coating, and having five and ten line grid patterns. The sunlight efficiency of these cells is about eight percent based on the total cell area of two square centimeters, and nine percent based on the active area of 1.8 square centimeters. The twenty minute diffused, five grid, non-coated cells seem to be only about one milliwatt lower in power than the coated cells. On the basis of this, the extra cost of application of such a coating is probably unwarranted (since cost is a prime concern here). However, as pointed out previously, the coating may not be optimized so that still greater power gains might be attainable through proper use of such a coating.

It is especially interesting to note that the forty-five minute diffused cells do not seem to be as far below the shallower diffused cells in power output as was observed for the P/N cells fabricated during the

second report period. Whether the previous results were due to processing variations or due to the type of material used to fabricate the cell (low resistivity, polycrystalline, n-type) remains in question.

The results of the N/P experiments continue to be quite encouraging. Cells having a sunlight efficiency of nine percent or greater (based on a 1.8 square centimeter area) now have been fabricated from both 10 ohm centimeter P, and one ohm centimeter N type polycrystalline material. (Actually, a cell having a sunlight efficiency of greater than ten percent has been fabricated from the latter material). Additional work is needed, however, before the various cell parameters can be optimized in order to bring efficiencies and yields to a still higher value.

CONCLUSIONS

The additional mirror which has been added to the concentrator system provides uniform concentration across the internal working area and increases the available intensity range to about 5 gm cal/cm^2 min.

The sunlight power predictions made on the basis of tungsten measurements during the P^+/N bivariable experiment have been verified and found to be accurate to within 5 percent.

A general equation for the determination of the total solar cell series resistance from a knowledge of the magnitude of the component resistances has been developed. This equation has been utilized to predict the total series resistance of N^+/P and P^+/N cells. The theoretically determined series resistance was found to be in very good agreement with experimentally measured series resistance values of high efficiency P^+/N and N^+/P cells.

The results of the P^+/N and N^+/P bivariable experiments have been analyzed and optimum cell designs have been chosen for solar cell operation in a terrestrial environment at normal and concentrated solar intensities.

Cells have been fabricated,utilizing polycrystalline p-type material having a resistivity in the ten ohm centimeter range,with sunlight efficiencies of greater than nine percent based on an active area of 1.8 square centimeters. This work has now shown that sunlight efficiencies of about 9% are obtainable for both N^+/P and P^+/N polycrystalline solar cells.

PROGRAM FOR NEXT INTERVAL

The main effort during the coming period will be placed on the pilot line production of 500 P^+/N and 500 N^+/P solar cells and the yield evaluation of these cells.

IDENTIFICATION OF KEY TECHNICAL PERSONNEL

The following engineering hours of work were performed during this reporting period.

M. Wolf	78 hours
E. Ralph	203 hours
P. Berman	434 hours
R. Handy	254 hours
G. Rolik	244 hours
S. von Szeremy	400 hours
T. Downey	16 hours
W. Pirtle	8 hours

There were also 922 hours of work performed by various other Heliotek personnel, such as Engineering Aides, Technicians and Draftsmen in collecting and presenting the data contained in this report.

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Heliotek, Division of Textron Electronics, Inc.
12500 Gladstone Avenue
Sylmar, California
HIGH EFFICIENCY SILICON SOLAR CELLS
Paul A. Berman, Roland J. Handy, and Geza P. Rolik

Third Quarterly Report, December 15, 1962 to March 15, 1963
USAERDL Contract DA36-039-SC-90777
Order No. 1091-PM-62-93-93 (4213), Unclassified Report

An additional mirror has been added to the solar concentrator equipment so that it is now possible to make solar cell measurements at approximately 5 gm-calories/cm^2 min solar intensity. The concentrator was used to verify the sunlight power predictions made from tungsten power measurements during the P^+/N bivariable experiment.

A general equation has been developed for the theoretical determination of the total cell series resistance from a knowledge of the values of the component resistances. The equations have been utilized to predict the series resistance of production type N^+/P and P^+/N cells. The predicted values were 0.73 ohms and 0.38 ohms for N^+/P and P^+/N cells respectively while the experimentally determined series resistances for high efficiency cells of these types were 0.74 ohms and 0.42 ohms respectively.

The results of bivariable experiments involving optimization of P^+/N and N^+/P cells for operations in a terrestrial environment under normal and concentrated solar intensities have been evaluated. On the basis of this analysis the optimum design for P^+/N cells requires a fifteen minute diffusion time and an eleven line grid pattern while the optimum N^+/P cell design requires an eighty minute diffusion time and an eleven line grid pattern.

Cells fabricated from p-type polycrystalline material having a resistivity of 10 ohm centimeters were evaluated for various cell designs. Cells having a sunlight efficiency greater than 9% based on an active area of 1.8 square centimeters were fabricated.

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2. Effect of High Concentration Ratios on Silicon Solar Cells
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